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Observing Spectral Response Differences In Freshwater Lakes Using Remote Sensing Technology

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OBSERVING SPECTRAL RESPONSE DIFFERENCES IN FRESHWATER LAKES USING REMOTE SENSING TECHNOLOGY

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Nutrient pollution is a growing issue around the world. The excess nutrients going into aquatic ecosystems allows phytoplankton to thrive and form algal blooms. Algal blooms can be hazardous to humans, wildlife, and destroy aquatic ecosystems. They also are costly to monitor and control. This study uses remote sensing to observe the spectral differences in lakes, specifically one that experienced an algal bloom, Lake St. Clair. It was also compared to a lake with exceptional water quality, Lake Tahoe. The objective was to see how the two differed spectrally and determine if remote sensing is a viable option for monitoring algal blooms. Data was gathered via the MODIS instrument on the Terra satellite. The images were analyzed, stacked, and pixels were chosen. The data from these pixels were exported to make graphs and visually represent the findings. The green band reflectance had significant results, showing higher values in the algal bloom compared to outside the bloom and in lake Tahoe. The APPEL index was also utilized, and it showed a significant increase during the time of the bloom as well. Remote sensing was found to be a viable option for monitoring algal blooms, despite some limitations.

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Introduction.

As our population grows exponentially and food becomes scarcer, agriculture becomes even more important. But with increased farming and fertilizer use, comes nutrient runoff (Nitrogen & Phosphorus) into surface and ground water. These nutrients continue to collect as they move down watersheds and accumulate in large amounts. Nutrient pollution is one of America's most widespread, costly, and challenging environmental problems (Harmful Algal Blooms, 2019). Phytoplankton, or algae, thrive and create algal blooms in aquatic areas that have high amounts of nutrients, warm weather, and moderate wind. Algal blooms will continue to rise in occurrence as global temperatures increase and ag runoff continues to go into our aquatic systems (Kislik, Dronova, Kelly, 2018). These pose health issues and ecosystem problems. Some algal blooms contain toxic algae or dense accumulations of non-toxic algae that can harm humans and wildlife and can result in habitat alteration and oxygen depletion (Ghatkar, Singh, Shanmugan, 2019). These algal blooms can be managed with proper prevention and treatments, but it is costly and time consuming. The purpose of this study is to use remote sensing to observe the spectral response differences between Lake St. Clair in Michigan during an algal bloom and one of the worlds least polluted lakes, Lake Tahoe in California.

Phytoplankton is a photosynthetic organism that floats on the upper layer of bodies of water. Algae share some traits with plants, such as the uptake of nitrogen and phosphorous and the inclusion of chloroplasts to make use of light energy from the sun. The presence of algae is not necessarily detrimental, but large algal blooms or the presence of toxic algae can be very harmful to ecosystems. When containing toxic algae, it is generally referred to as a harmful algal bloom (HAB) or a “red tide”. Another term that is often associated with algal blooms is eutrophication. Eutrophication is an increase in the rate of supply of organic matter to an ecosystem (Nixon, 1995). The organic matter that is being referred to is the algal bloom that contains a vast amount of algae which thrive on large inputs of nitrogen and phosphorus.

Algal blooms contain compounds that have strong odors and cyanotoxins, which are harmful to species. Some of these cyanotoxins can cause allergic and/or respiratory issues, attack the liver and kidneys, or affect the nervous system in mammals including humans (Buxton, n.d.). In order to prevent these health issues, popular recreational areas are being shut down more frequently in order to protect civilians. Not only do harmful algal blooms affect humans, they essentially destroy the aquatic ecosystem that is present. When the algae die and are decomposed by bacteria, the water below the surface is depleted of oxygen which in turn harms fish and other marine life (Klemas, 2012). This creates what is known as hypoxia or “dead zones” in the water. Since algal blooms are such a hazardous and costly phenomenon, it is critical that they are monitored and prevented as much as possible.

Algal blooms also come with a large monetary cost. A study calculated potential annual value losses in recreational water usage, waterfront real estate, spending on recovery of threatened and endangered species, and drinking water. The combined costs were approximately $2.2 billion annually as a result of eutrophication in U.S. freshwaters (Dodds et. Al., 2009). There are many potential costs that were not included in this study as well such as losses due to health issues, tourism, fisheries & hatcheries, etc. With the frequency and severity of algal blooms increasing, the costs are likely to increase as well. Remote sensing technology can also save a significant amount of money that would have otherwise been spent on gas, laborers, and more.

With the use of remote sensing technology such as the Terra satellite system and MODIS instrument, one can view the world in ways that they cannot from the ground. Data collection also tends to be more efficient when compared to field measurements. Remote sensing of lakes more cost effective because of its reductions in manpower and travel costs (Brezonik, Menken, Bauer, 2005). These satellites collect various kinds of data depending on the type of instrument. In general, the satellites capture and measure the light being reflected from the earth at wavelengths specific to their instrument's spectral resolution. Depending on the satellite and its sensor, one can see emissions of the electromagnetic spectrum which are not visible to the human eye. Although there are some things that need to be corrected for such as clouds and other particles in the atmosphere, the information retrieved by these instruments is accurate and useful. Objects on Earth reflect more light at some wavelengths than others, thus having a rather unique spectral response depending on many characteristics. By observing the spectral response of certain targets such as vegetation, we can learn a lot about the health of that area of vegetation that was examined.

MODIS 500m 8-day composite data was used based on the spatial and temporal resolution considerations. Landsat 8 was initially considered as a data source, but a large number of cloudy images required an alternative approach. While Landsat has a higher spatial resolution, it has a lower temporal resolution meaning that the images are only taken every 16 days for one location as opposed to MODIS' 1-day resolution. MODIS still encounters issues such as cloud cover as well, but to minimize that, 500m 8-Day composites are made. These 8-Day composites choose the best possible surface reflectance values for each pixel in order to reduce the amount of atmospheric contamination in the images (MODIS/Terra Surface Reflectance 8-Day L3 Global 500m SIN Grid, n.d).

MODIS is a great instrument to use for this study because of its spectral and temporal resolution. MODIS has 36 bands of wavelengths that it picks up and five of which are in the visible region (MODIS Web, n.d.). With this data, certain qualities can be estimated and analyzed such as secci disk transparency (SDT), chlorophyll-a concentration, etc. Many studies focus on indices such as chlorophyll-a concentration and light absorption when it comes to phytoplankton (Wang, Lee, Mouw, 2017). In a sense, chlorophyll-a and SDT go hand in hand because with more algal cells in the water, the more turbid the water is. These can be estimated with the use of remote sensing, but for this study a few indices were utilized. One common index that is studied is the Normalized Difference Vegetation Index, also known as NDVI. Algae is seen as organic matter and has a green color which would is why it can be observed and treated as vegetation in remote sensing, although it is not ideal for water quality applications. NRGDI (Normalized Red Green Difference Index) is also examined. NRGDI is similar to NDVI but uses the red and green bands instead of near infrared and red bands. An index that is more geared for algal blooms is the APPEL (APProach by Elimination) index. In a study that evaluated the effectiveness of certain indices, the APPEL Index performed well for estimating chl-a concentrations in lakes compared to other indices but is more responsive to larger algal blooms (El-Alem et. Al, 2012). Besides looking at indices, simply observing how the green band surface reflectance changes could be useful. While it is not really a calculated index like the others, it can still be a decent indicator of the presence of an algal bloom.

Lake St. Clair in Michigan is the experimental lake in this study. This lake was chosen because of its size, algal bloom history, and data availability. The surrounding watershed that leads to Lake St. Clair has many inputs and most of which are agriculture areas but also some urban inputs as well. In late July of 2015, Lake St. Clair experienced a rather large algal bloom

(EGLE Water Lakes & Streams Water Quality Monitoring, n.d.). This will be the primary focus of this experiment. Lake Tahoe in California is known for its exceptional water quality. This acts as the control of this study to which Lake St. Clair was be compared to. The two lakes were analyzed to see how they differ spectrally. Since the water quality is different in both lakes, it was expected that there would be a difference in spectral response when comparing the two. In Lake St. Clair, the hypothesis was that the indices would be higher than Lake Tahoe and would show a major increase during the time of the bloom. For Lake Tahoe, which has consistently higher water quality, it was expected that there will not be much of a change in the specific index over time because it is not experiencing an algal bloom.

Most of the remote sensing research done on algal blooms has been done in oceans especially along the coast. There has been a significant amount a bit of success in monitoring harmful algal blooms with remote sensing in the ocean and that information could be useful when trying to relate it to inland bodies of water. Along with that information, there have been some studies done on freshwater lakes around the globe. A previous study used 10 Landsat images acquired over 25 years to evaluate water clarity trends in ~450 lakes across the metropolitan area of Minneapolis-St. Paul, MN (Brezonik, Menken, Bauer, 2005). This is just one example of how remote sensing technology can be used to monitor water quality.

Research with remote sensing is important and applicable for many reasons. Not only does remote sensing give us a “birds eye view” of the world, but it also lets us track certain areas of the world over time. Some advantages to remote sensing are the spatial resolution, temporal resolution, and the ability to track many lakes at once (Koponen, 2002). The ability to observe targets on a large scale and being able to revisit it often is a huge advantage to remote sensing. As opposed to regular in-situ sampling, one can also observe lakes that may be unavailable to sample traditionally. Tracking bodies of water or streams with remote sensing technology can help us monitor and be proactive when it comes to the quality of our water systems. Doing this could help us tackle these harmful algal blooms that we are experiencing all around the world.

Materials & Methods.

The research design of this study is like that of a descriptive research study. Along with observing the spectral characteristics of the lakes, there is also a comparative analysis aspect to it. This comes from having an experimental lake (Lake St. Clair) and a control lake (Lake Tahoe). The descriptive aspect is observing how each lake changes in index values over time. The comparative aspect comes from seeing how the two lakes differ in those time series.

To start, the task was to find a lake that was the proper size and had experienced an algal bloom within the last ten years or so. Another rather big factor was that it was located around agricultural land since there is a correlation to algal blooms and fertilizer runoff. Lake St. Clair in Michigan was the perfect fit since it experienced an algal bloom in the summer of 2015. The next step was to find a lake with exceptional water quality as a control lake. Lake Tahoe is known as one of the purest lakes in North America. It is also rather large, so it seemed right to choose this lake. The size of the lake is important because if it is too small, then the spatial resolution would likely skew the data.

One of the more difficult parts was trying to decide on which satellite to use for this experiment. There are many things that come into play when trying to decide on the right one. Some of the biggest factors are the spectral resolution, spatial resolution, temporal resolution, cloud cover, etc. Initially, Landsat 8 was the satellite that was used but later in the research process, MODIS seemed to be a better fit for this study due to the 1-2-day temporal resolution compared to Landsat's 16-day temporal resolution. MODIS had 8-day composite images which creates one image and chooses the best pixels out of the 8 days for every pixel. This helps to eliminate atmospheric contamination but is still not always perfect. The MODIS images were collected from Earthdata Search which is powered by NASA. All the 2015 8-day composite images were gathered for 2015 for both Lake St. Clair & Lake Tahoe. Then, all the images were inspected to see which ones had the least amount of cloud contamination. For lake St. Clair, 15 images were used for processing ranging from day 105 to day 297. Lake Tahoe had more clear images which totaled to n = 18.

ENVI, a software package specifically designed to view and analyze remote sensing data, was used to perform the analysis. What is useful about ENVI is that each pixel can be examined, and certain wavelengths or bands can be changed to appear differently which can greatly improve analysis. For this experiment, ENVI was the main software for image processing and analysis. To start, the first index used was NDVI. While it is mainly used for land and vegetation applications, it can potentially be useful for tracking algal blooms since they share similar properties. With the use of ENVI and the Band Algebra tool, an NDVI version of every image was created with the equation (B2-B1)/(B2+B1). This same thing was done with each of the other indices used (NRGDI, APPEL, and the Green Band reflectance). Once each image also had a corresponding image with the four different indices, a multi-temporal stack was created using the Layer Stacking tool in ENVI. The stacked image contained the index images as individual layers, thus creating a time series of index images. After creating a stack for every index, it was then time to choose the pixels to use.

In Lake St. Clair, two pixels were observed. One pixel was in the middle of the lake, away from the bloom. The other pixel was within the algal bloom. Ideally, random sampling would make it more scientifically credible, but due to the atmospheric issues it was not ideal for this study. One pixel from Lake Tahoe was utilized as well. Since there is no algal bloom present, a pixel that was near the southern shore was chosen. After the pixels were chosen, the data for each index at each pixel was then exported via ASCII file. These were the imported to Microsoft Excel to create time series graphs.

There was a total of six scatter plots with lines created in order to show how the valid indices changed through time and in each lake. On the x-axis is the range of days that were chosen. The dates for the two lakes were slightly different but generally ranged from day 89 (March 29th) to day 300 (October 26th). The y-axis shows the index value such as the APPEL index value. This helps show how the specific indices change through time and can help determine if there are any differences during the algal bloom. Since the most significant and valid results were from the green band reflectance and the APPEL index, the focus was put on those two.

Results.

There were some significant findings within the data gathered. The NDVI and NRGDI indices had values that were unusual numbers that were outside of the +1 to -1 threshold. Because of these anomalies, the focus was put on the green band reflectance and the APPEL index. The green band surface reflectance showed a significant increase within the algal bloom in Lake St. Clair around the 209th day of the year, which is July 27th (See Figure 1). The values earlier in the year stayed between 0.035 and 0.06 but then greatly increased to a maximum of almost 0.08. After that, the values began to decline where they returned to their values around 0.05.

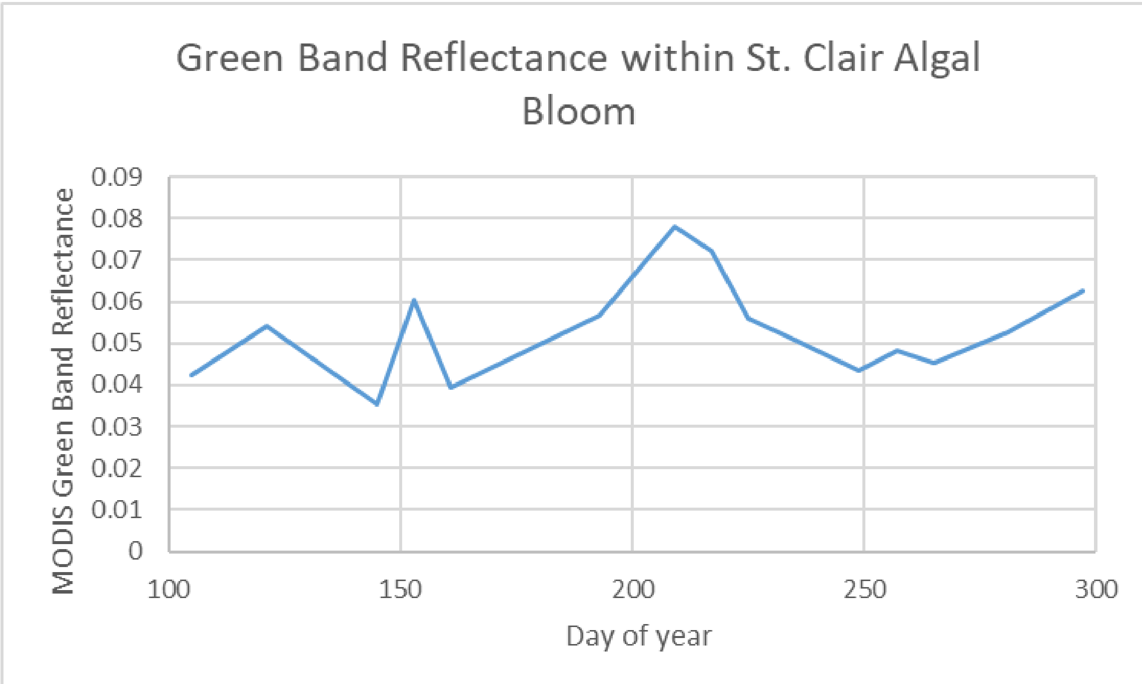

Figure 1. Green band reflectance in the algal bloom of Lake St. Clair throughout 2015.

Looking at values of green band reflectance outside of the bloom, or in the middle of Lake St. Clair, there is a clear difference compared to within the bloom. Other than the very first date, which is day 105, all the values stayed within a range of 0.018 – 0.04. Day 105 was likely an anomaly due to cloud cover or the atmospheric correction that MODIS does. This led to a value of ~0.058. Figure 2 gives a visual representation of how the green band reflectance changes throughout the year in the middle of Lake St. Clair. Figure 3 is a combination of the first two graphs to better show how the values are different inside the bloom compared to outside of it.

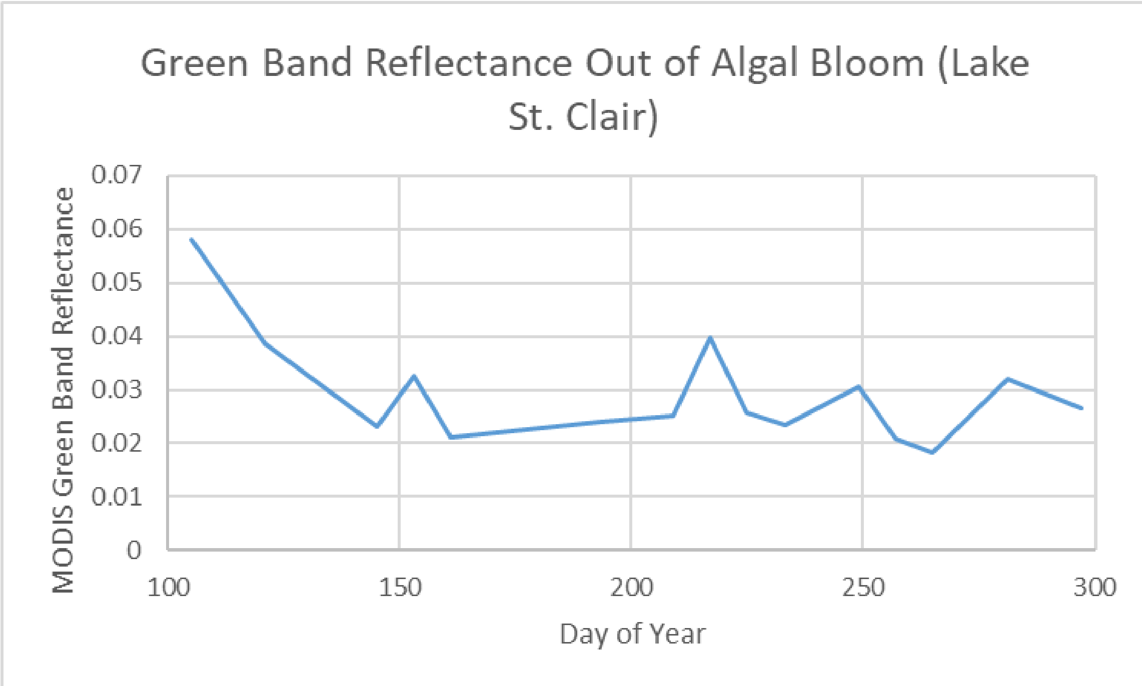

Figure 2. Green band reflectance out of the algal bloom in Lake St. Clair through 2015.

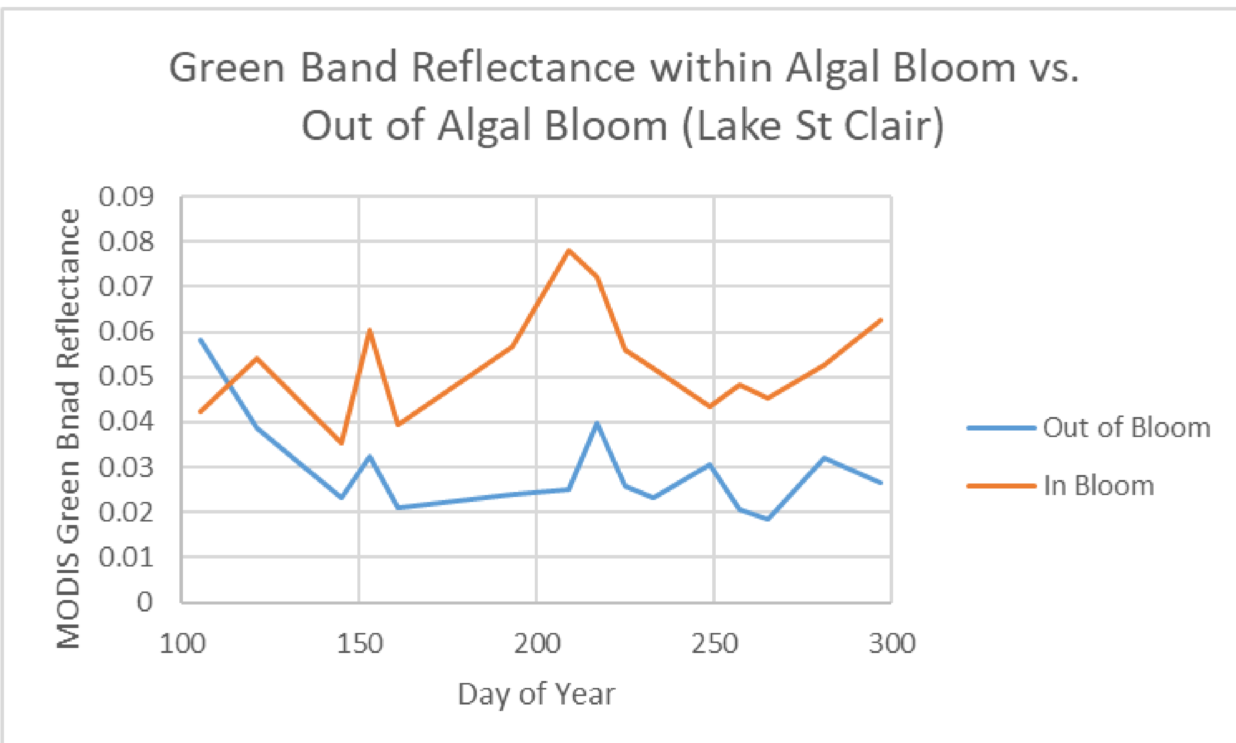

Figure 3. Green band reflectance within the algal bloom vs. out of the algal bloom in Lake St. Clair through 2015.

In Lake Tahoe, the green band reflectance has a lot smaller range of values and they are all close to zero (See Figure 4). The maximum value is 0.011 and the minimum is 0.001. There is not a trend, the values seem to increase and decrease, with the highest values in late July. Figure 5 combines both the Lake Tahoe green band reflectance with the Lake St. Clair in bloom green band reflectance. This helps give a better visual representation of how the two differ in not only magnitude, but also trends during the bloom.

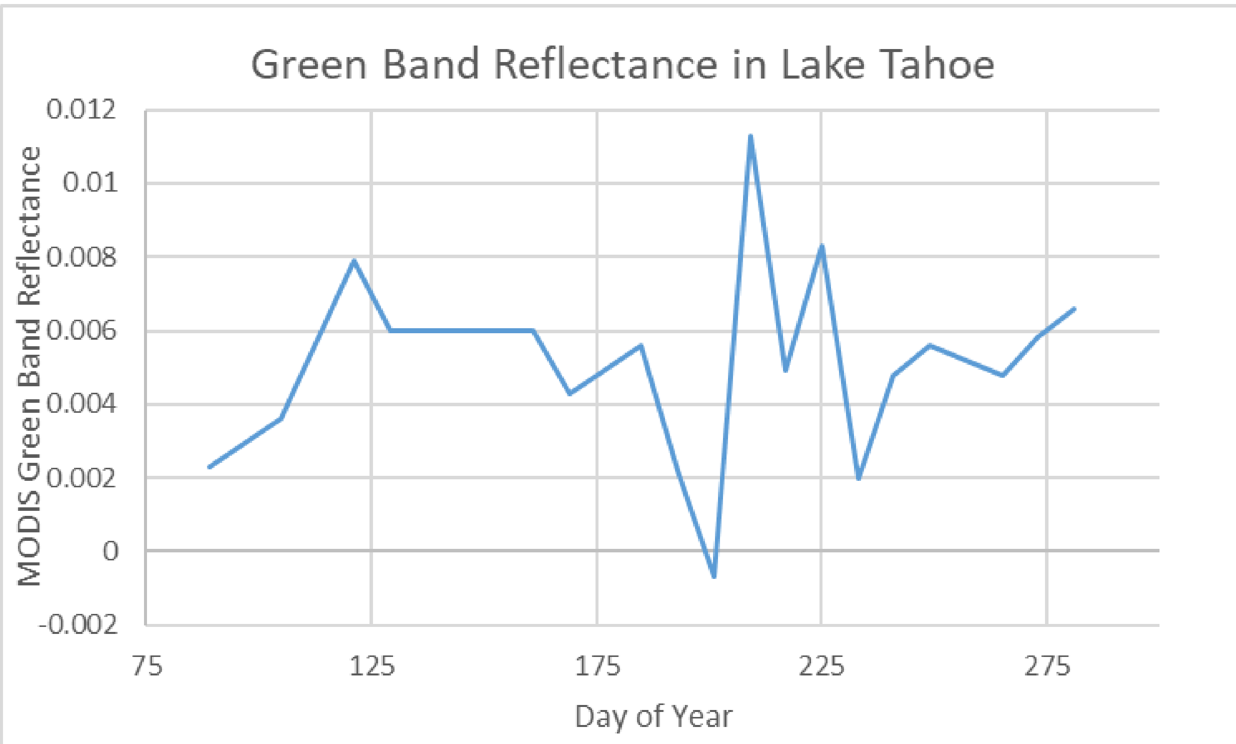

Figure 4. Green band reflectance in Lake Tahoe through 2015.

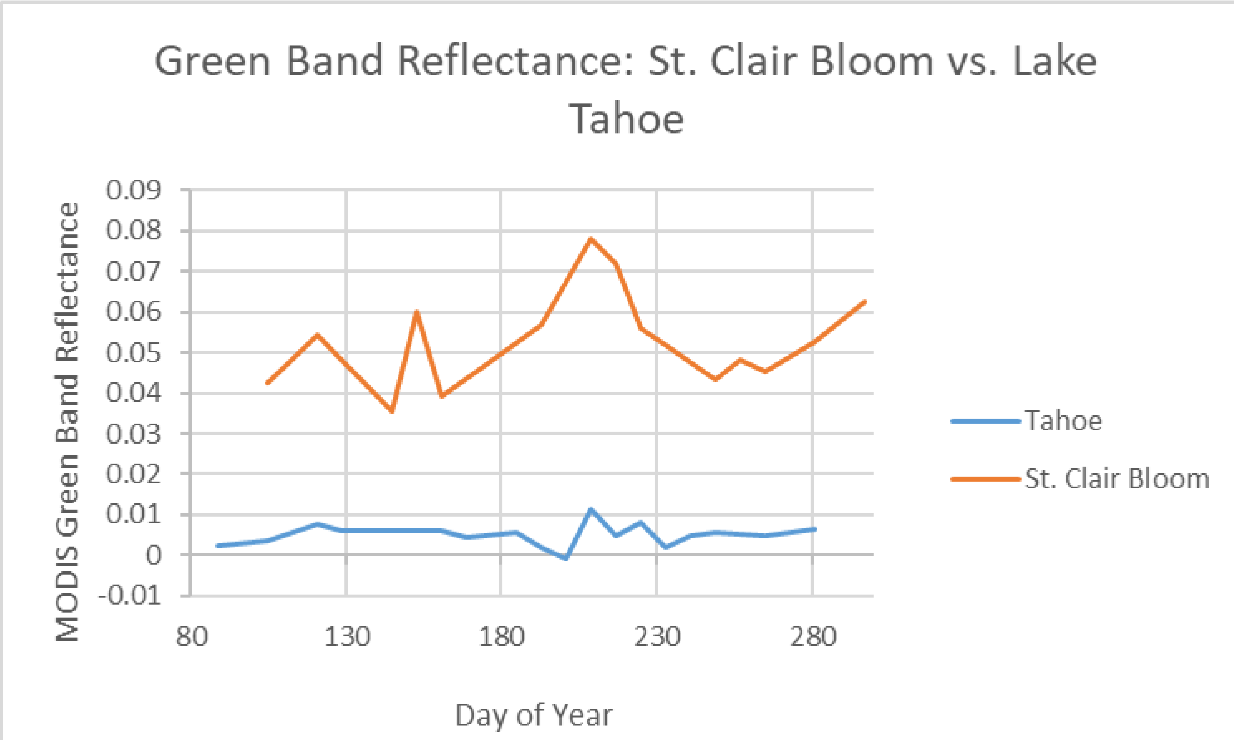

Figure 5. Green band reflectance through 2015 for Lake St. Clair in bloom vs. Lake Tahoe

The only index that showed significant data that was not too extreme, was the APPEL index. For both the Lake Tahoe data and the Lake St. Clair out of the bloom data, the values hover around zero. Lake St. Clair had more negative values overall but during the algal bloom, the APPEL value increased significantly to ~0.125. The range of APPEL values for the pixel within the bloom ranged from -0.05 to the peak of ~0.125. Figure 6 shows the APPEL data from all three pixels that were chosen combined into one graph.

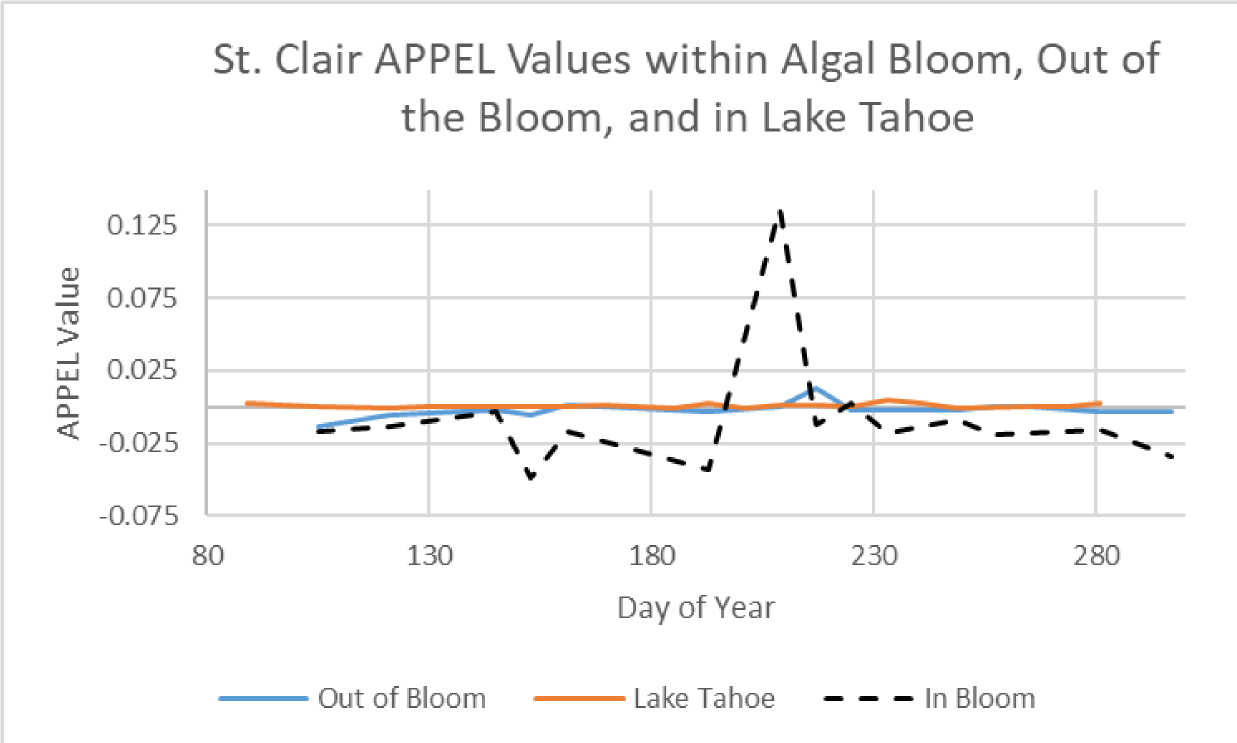

Figure 6. APPEL values for all three data points: In the bloom, out of the bloom, and in Lake Tahoe throughout 2015.

Discussion.

The green band surface reflectance showed the most significant results. There is a clear magnitude difference of the green reflectance within the bloom vs. outside of the bloom. Also compared to Lake Tahoe, the green band reflectance in the bloom is much higher. While this does not estimate anything like chlorophyll-a content, it is a good indication that there is a bloom present and when it is at its worst. Also, the green reflectance increases and reaches a peak when the bloom was at its worst, at the end of July. We also see this same trend in the APPEL data with a similar peak at the same time.

The APPEL index is more geared for algal bloom monitoring and estimating chlorophyll content. The only issue is that it is more sensitive at larger amounts of chlorophyll-a. That could explain why the values are negative for St. Clair within the bloom. Once the algal bloom was at its worst, the APPEL index values increased greatly and thus had a similar peak to the green band reflectance. This is likely because of there being enough chlorophyll present for the index to be pick it up and be significant. The data from outside the bloom and in Lake Tahoe had a much more steady and consistent range of values. They both were almost consistently around zero.

The nature of the 8-day MODIS composites likely had an impact on the results of some of the data. While they are made to eliminate a lot of atmospheric contamination, they still are not perfect and can have values that do not make sense or are extreme. Also, MODIS does try to correct a lot of the atmospheric issues and that could also have impacted the results. These reasons are likely the cause of why the NDVI values and NRGDI values were invalid. It also may explain the anomaly within the green band reflectance outside of the bloom in Lake St. Clair. Also, NDVI is mainly used for land applications, which is likely why it did not produce values within the threshold of +1 to -1. Many of the MODIS bands that were utilized are also mainly used for land applications, instead of water, hence the name of the satellite system, Terra. It may be wise to use bands that are more geared for water applications such as the Aqua satellite.

Conclusions.

The results of this study show that remote sensing can be an extremely helpful tool when it comes to monitoring algal blooms in lakes around the world. A major drawback is that there is a lot of advanced technology and analysis needed to properly estimate things such as chlorophyll-a. Cloud cover and other atmospheric contamination impact results and thus need to be eliminated to properly use remote sensing for these applications. In this study, the green band surface reflectance showed significant spectral differences when looking at pixels within an algal bloom, outside of the algal bloom, and in a lake with exceptional water quality. This is a good indicator that the green band reflectance can be used to monitor the presence of algal blooms. The APPEL index, which is more intended for algal bloom tracking, also showed a significant spectral response for the algal bloom. While it is better for larger blooms and higher chlorophyll content, it still provides evidence that it has potential for monitoring algal blooms.

For future research, there are some factors that could be changed to get better results and test new hypotheses. One would be to use an index that is more ideal for the size of the lake or the size of the algal bloom. This would improve accuracy and could better show the spectral response differences that are associated with algal blooms. Another way to improve this study would be to find daily images with the least amount of atmospheric contamination, as opposed to using 8-day composites. Also, potentially looking at data over multiple years instead of one year could be beneficial. Another option is to create models with specific inputs such as air temperature, water temperature, specific bands, etc. This could give a better understanding of what is impacting algal blooms and what the best way to monitor them is. Finally, using bands or satellites that are more ideal for water quality assessment would improve the quality of a study. Hyperspectral data could be a better option because of the ability to choose bands that are more defined and specific. Using a satellite more geared for water applications would likely be a better option but can also have limitations as well.

As we continue to see increasing amounts of agricultural productivity and how it is impacting our aquatic ecosystems, the importance of monitoring algal blooms continues to rise. Remote sensing offers a different view on the world and allows for more cost-effective monitoring. Although there are some limitations, it is still an extremely helpful tool that will continue to improve as technology and our knowledge continues to grow. By using remote sensing to monitor the health of our lakes and other water sources, we can maintain a more sustainable and healthier lifestyle for not only humans, but other wildlife as well.

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